

Excitation of Solar Oscillations

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Collaborators

- Observations & Simulations:
 - Thomas Rimmele
 - Louis Strous
- Simulations add:
 - Åke Nordlund
 - Robert Stein

Broad Conclusions

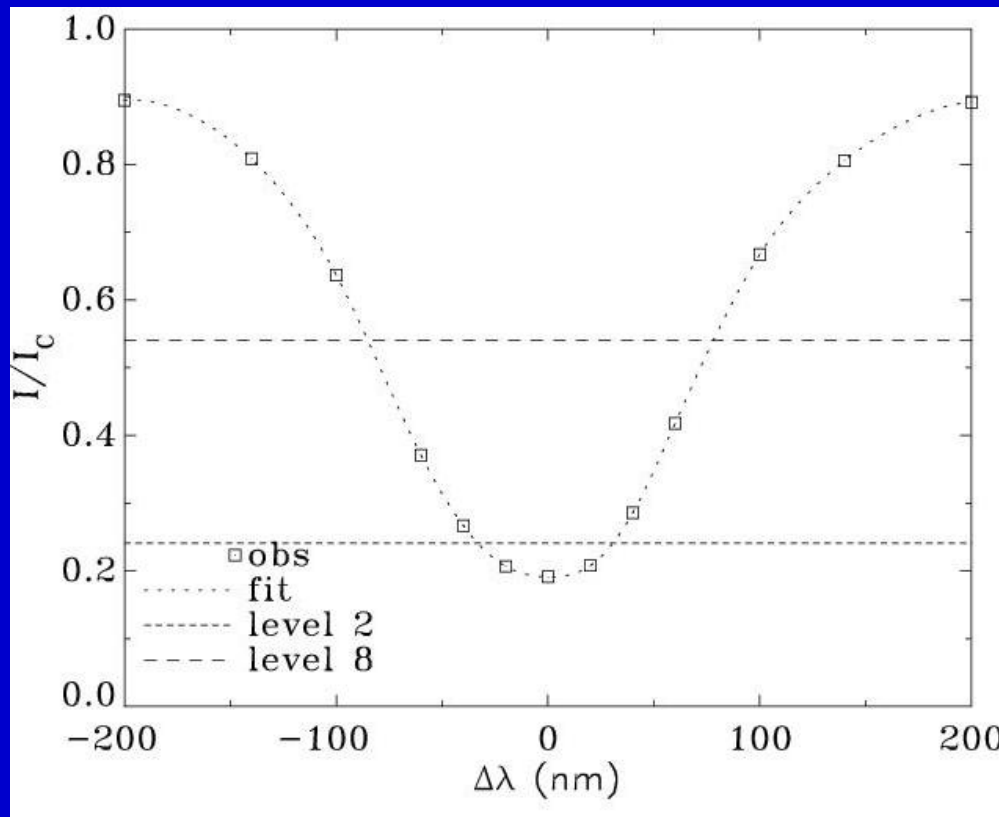
Observational Results:

- Excitation of solar oscillations closely associated with seismic events caused by a rapid cooling and collapse in the dark lanes of the convective layer, rather than the overshooting of turbulent convection itself
- Source seismic events is monopole
- Seismic events pump power into the normal modes
- Power in events sufficient to drive p-mode
- Seismic events weakened in areas of even weak magnetic field
- Many short-lived Ca II K bright points driven by seismic events

Simulated Results:

- Collapse of weak, bring granules causes large seismic events

Observing the 5434 Å Line with DST Fabry-Perot

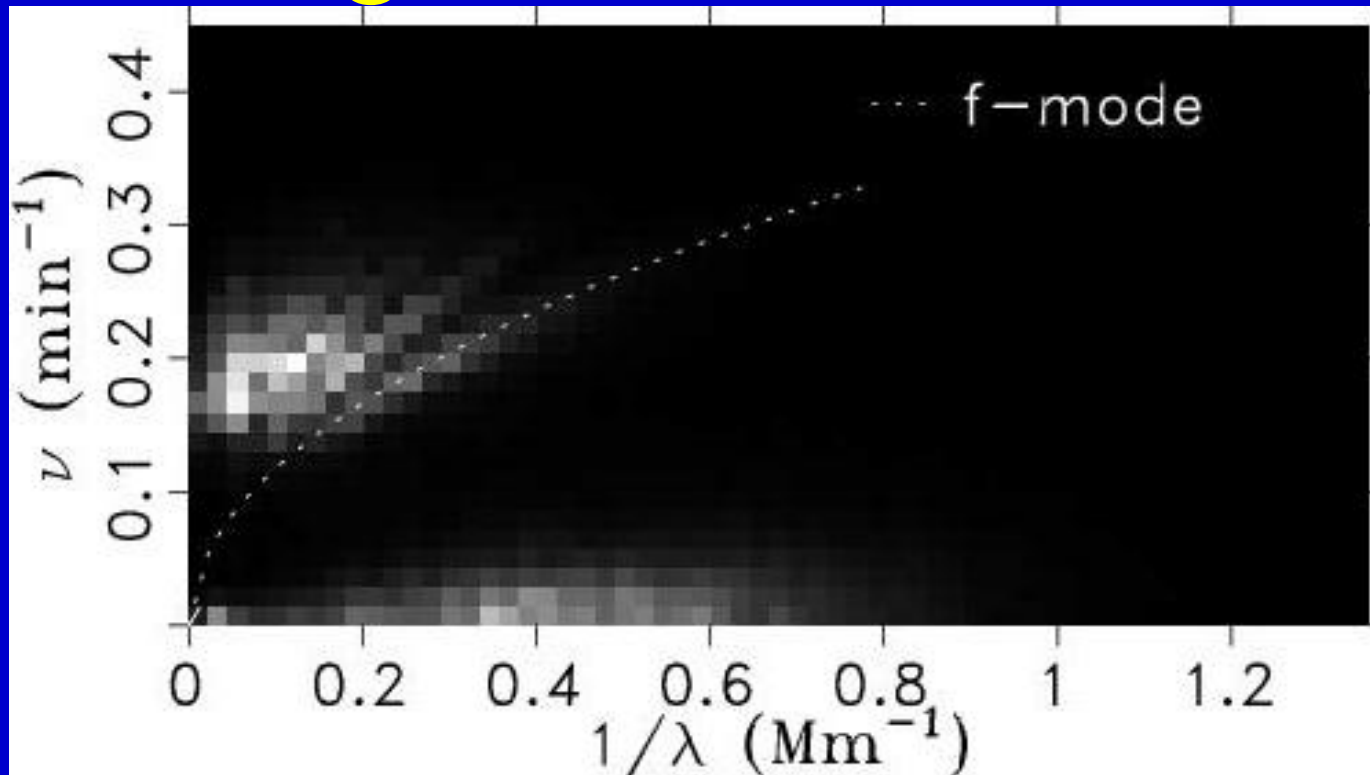


- 60" x 60" of quiet sun
— guided by H α
- 0.19 " pixels
- ~220 ms exposure
- 14 wavelength points
- 32.5 s steps for 65 min
- Broad band images from 2nd CCD
- Use correlation tracker and destretching
- Good/excellent seeing

Data Reduction

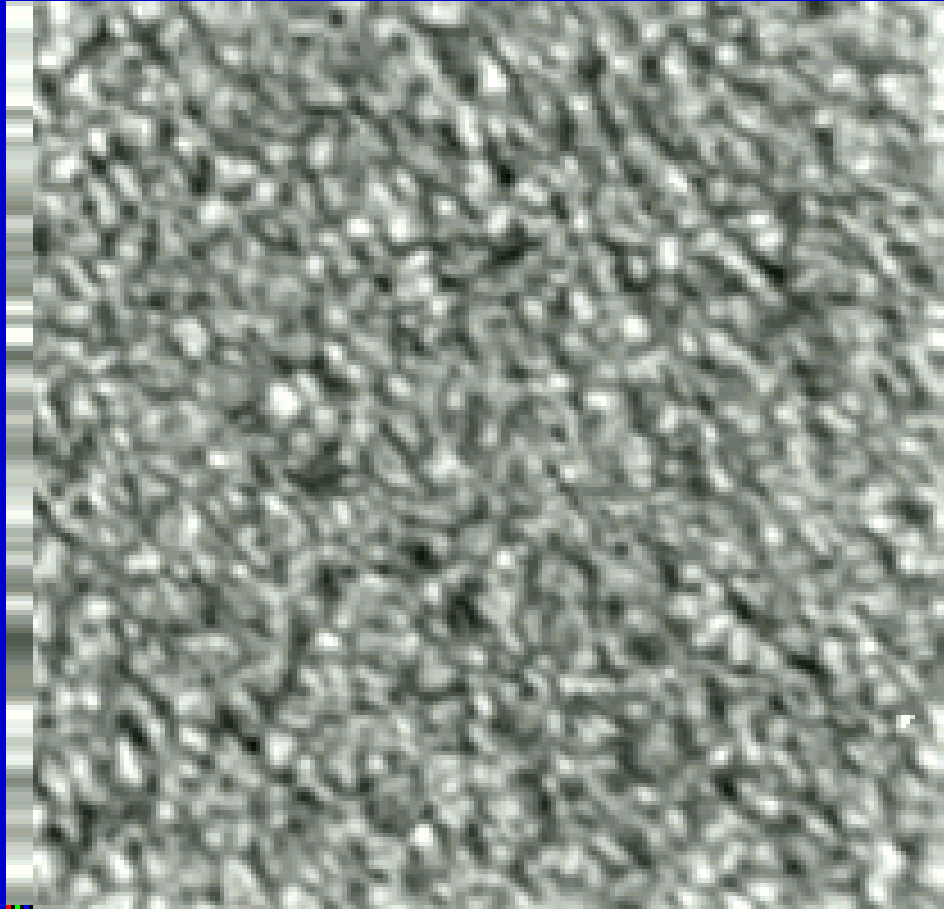
- $v(x,y,z,t)$ at 10 intensity levels in line
- k - ω diagrams at 10 photospheric altitudes
- Filter out power outside 5 minute band
- Hilbert transform (velocity amplitude and phase)
- Calculate “seismic flux”, u , to superimpose on granulation
- $u \propto [V^2/\omega][\Delta\phi/\Delta z]$, $\Delta z \sim 180$ km
- u needed to distinguish p-modes from seismic events, since they co-exist in the k - ω diagram

k- ω Diagram for 65 min Dataset



- Power in p-mode region that is not evanescent —this is seismic event power — there is negligible power above the acoustic cutoff ($> 0.4 \text{ min}^{-1}$)
- Power in convective regions yields same convective field pattern as the 2nd broadband CCD

Upgoing Seismic Flux Superimposed on Granulation

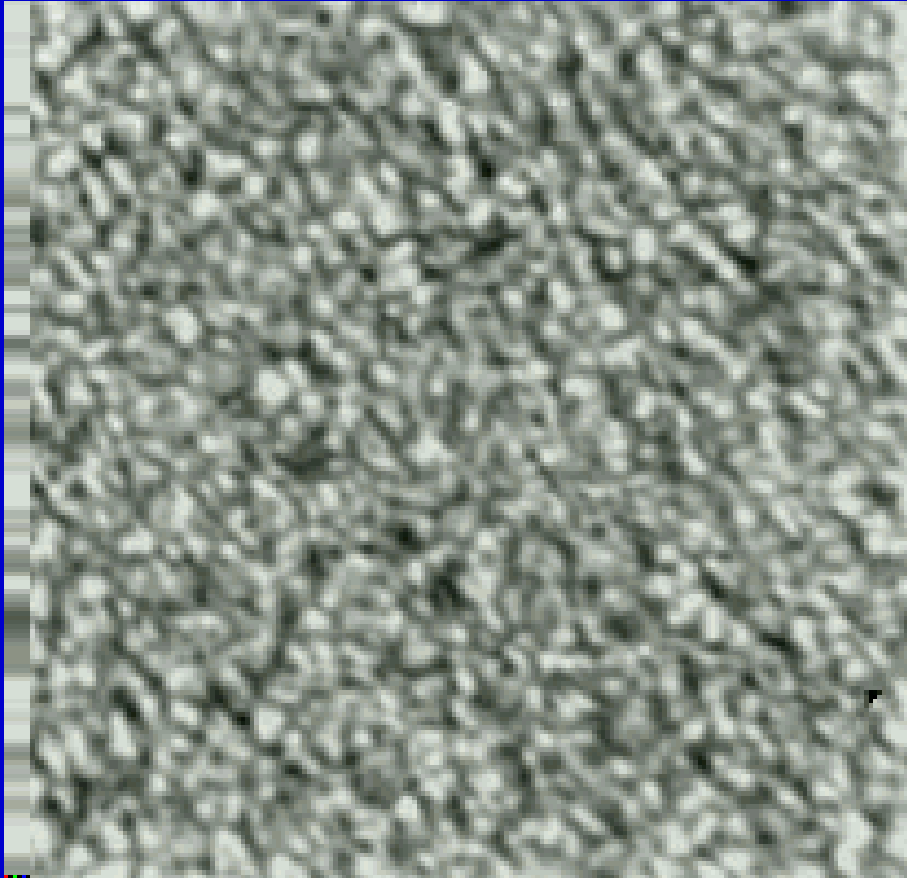


- 65 min dataset
- Seismic events confined to dark lanes (only apparent in high resolution)
- Scaling power in FOV to whole Sun, and accounting for depth of source, yields more than sufficient power to drive the p-mode spectrum
- Most flux lost to photosphere

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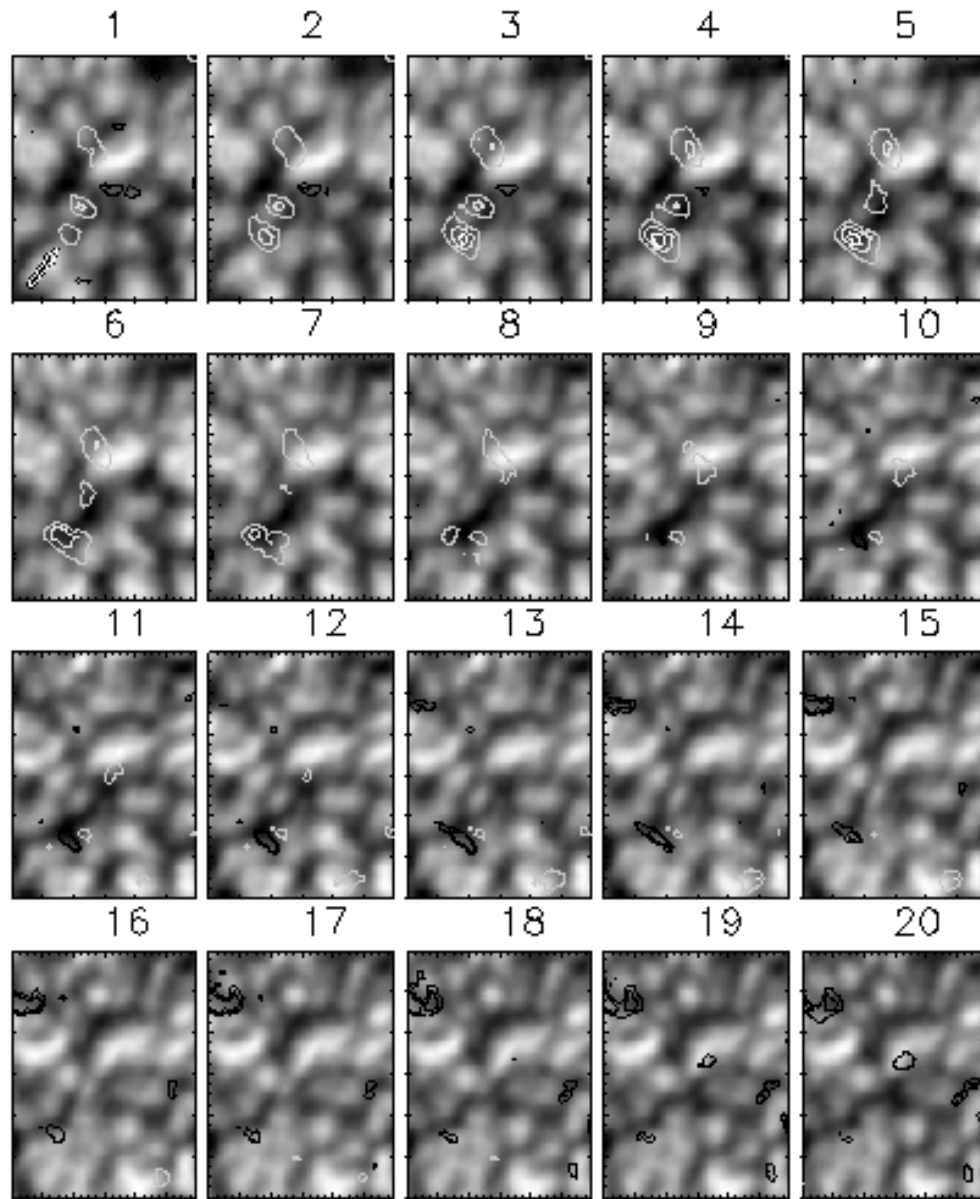
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Upgoing Seismic Flux Superimposed on Granulation



- Same as previous movie, except that the seismic flux is shown with dark contours

High Resolution —Follow Event Indicated by Arrow in First Frame

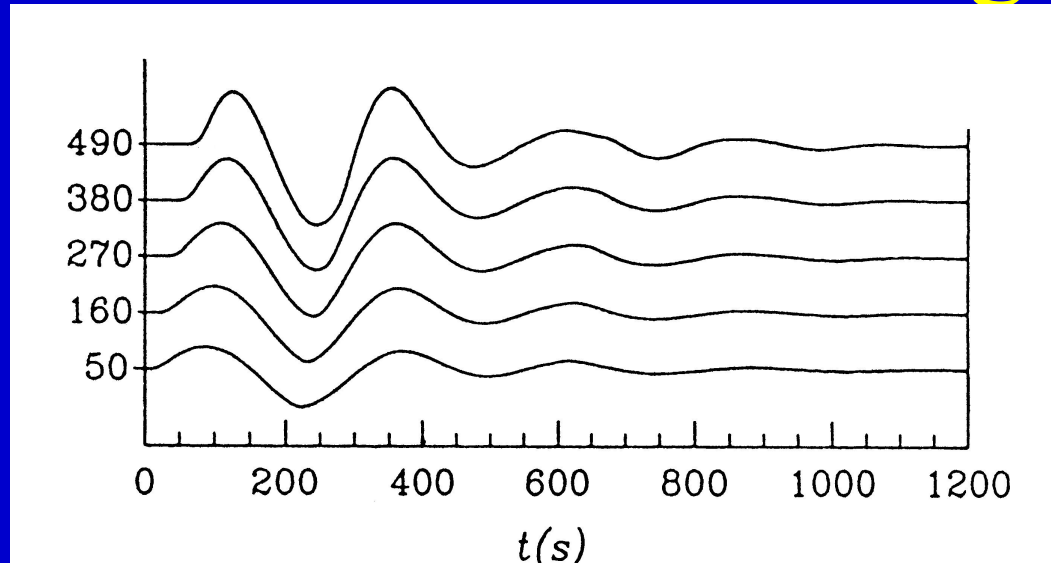


- 20 8" by 10" panels in 32.5 s timesteps
- White contours (0.6 , 1.0 , & 1.4×10^8 ergs/cm²/s) for upgoing flux
- Black contours (-0.2 & -0.5×10^8 ergs/cm²/s) for downgoing flux

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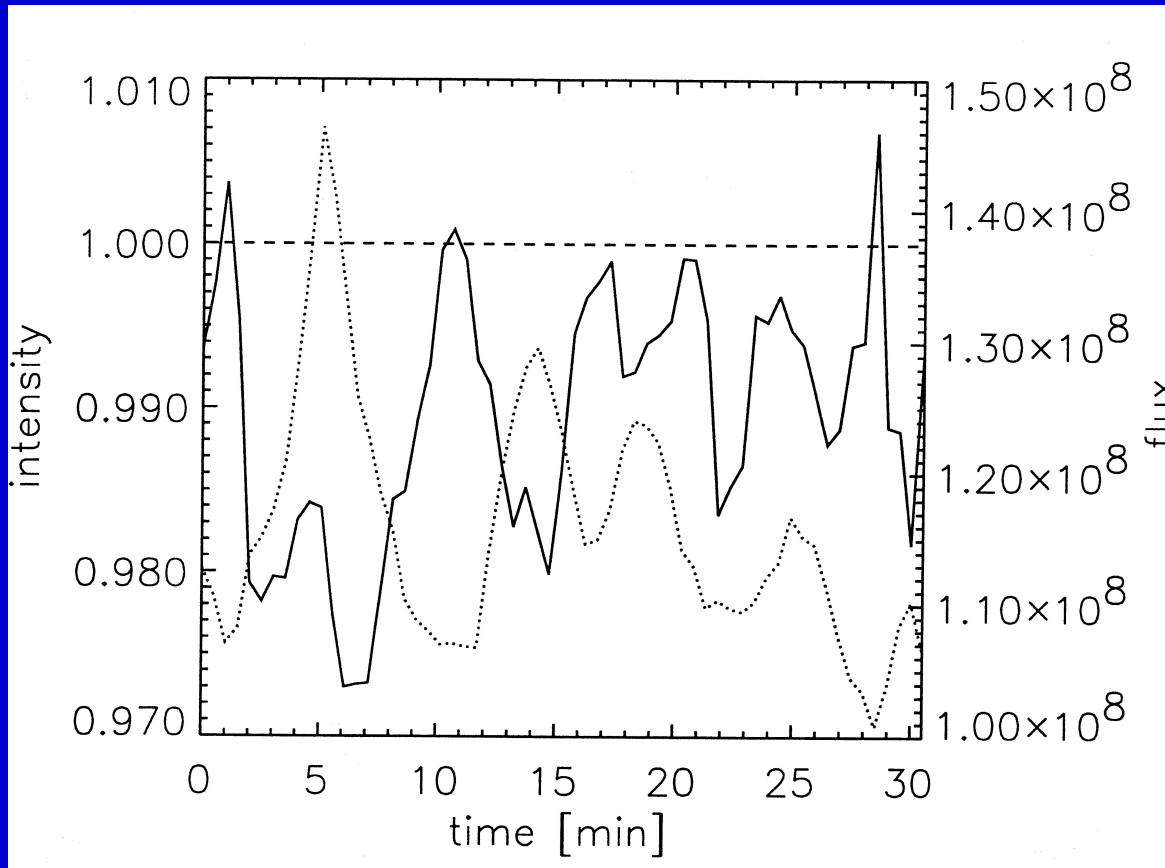
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Photospheric Response, $V(t)$, to Subsurface Forcing



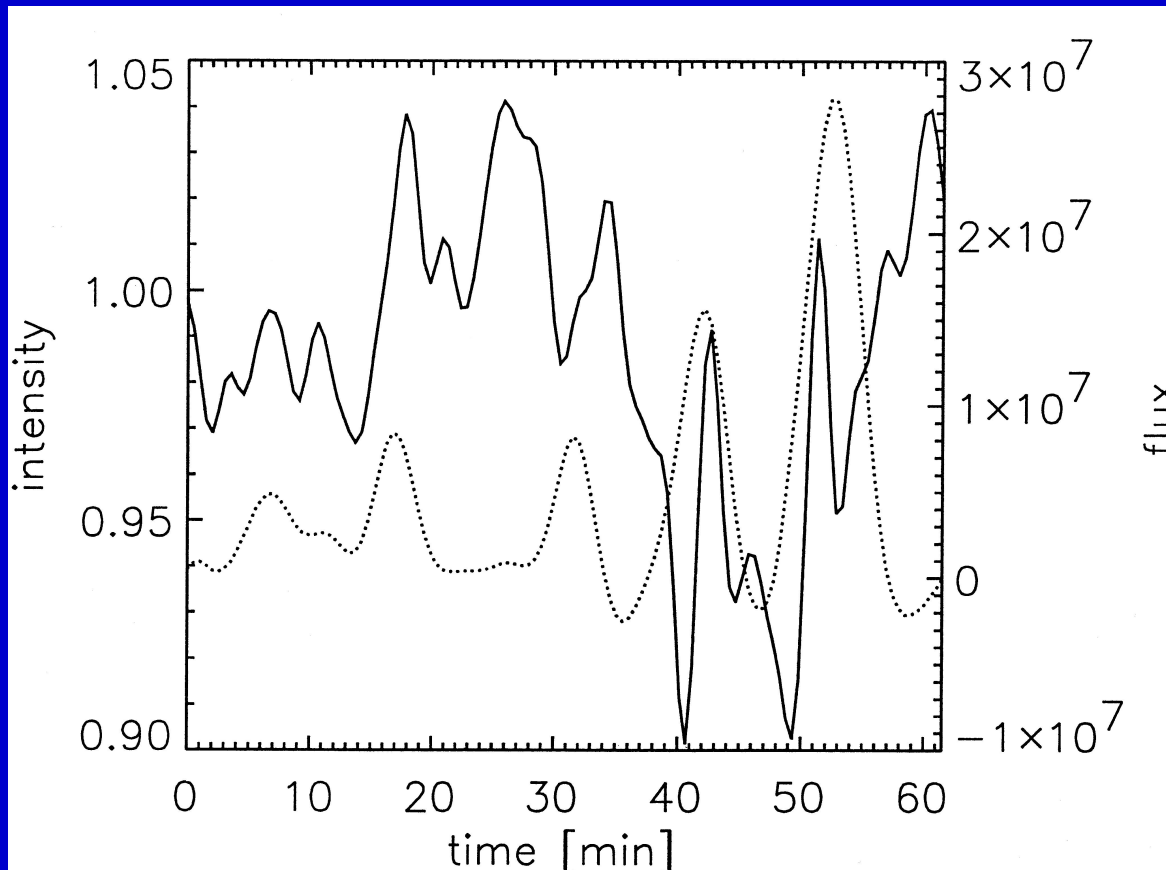
- Primary disturbance at $z \sim -100$ km for ~ 200 s
- Lamb-like waves result
- Damping & reflection combine to give “downgoing” wave
- Atmospheric response key to decoding subsurface action

Time Evolution of Large Flux Events Superimposed on Local Granulation



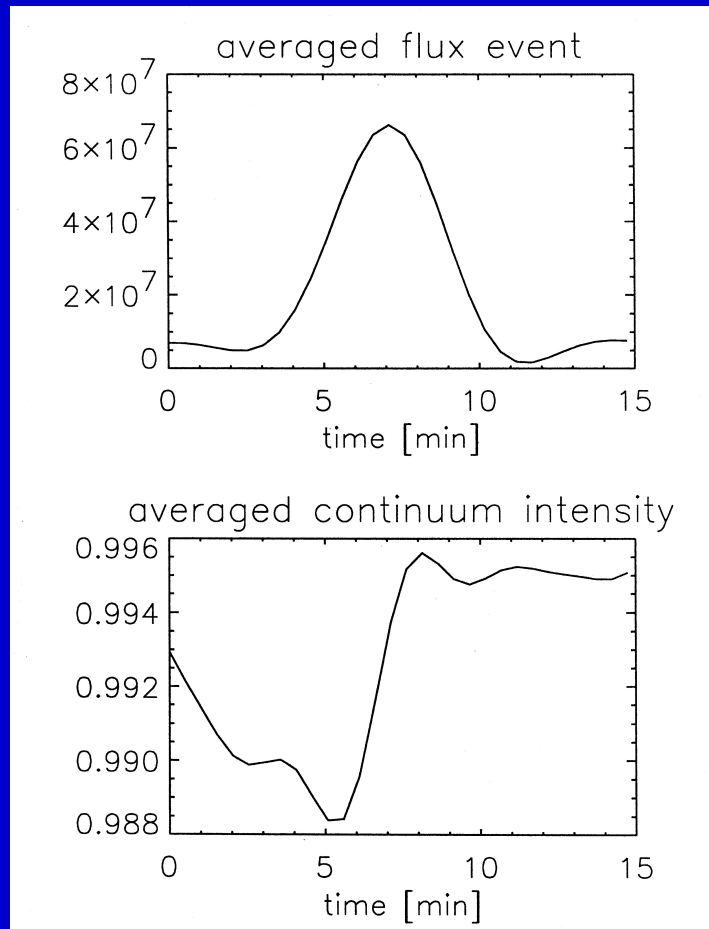
Mean granular intensity (solid line) at location of large flux vs. time. Dotted line is corresponding flux.

Acoustic Flux Events at One Spatial Point Superimposed on Local Granulation



Time evolution of acoustic flux (dotted line) and granular intensity (solid line) vs. time. Two large flux events near end

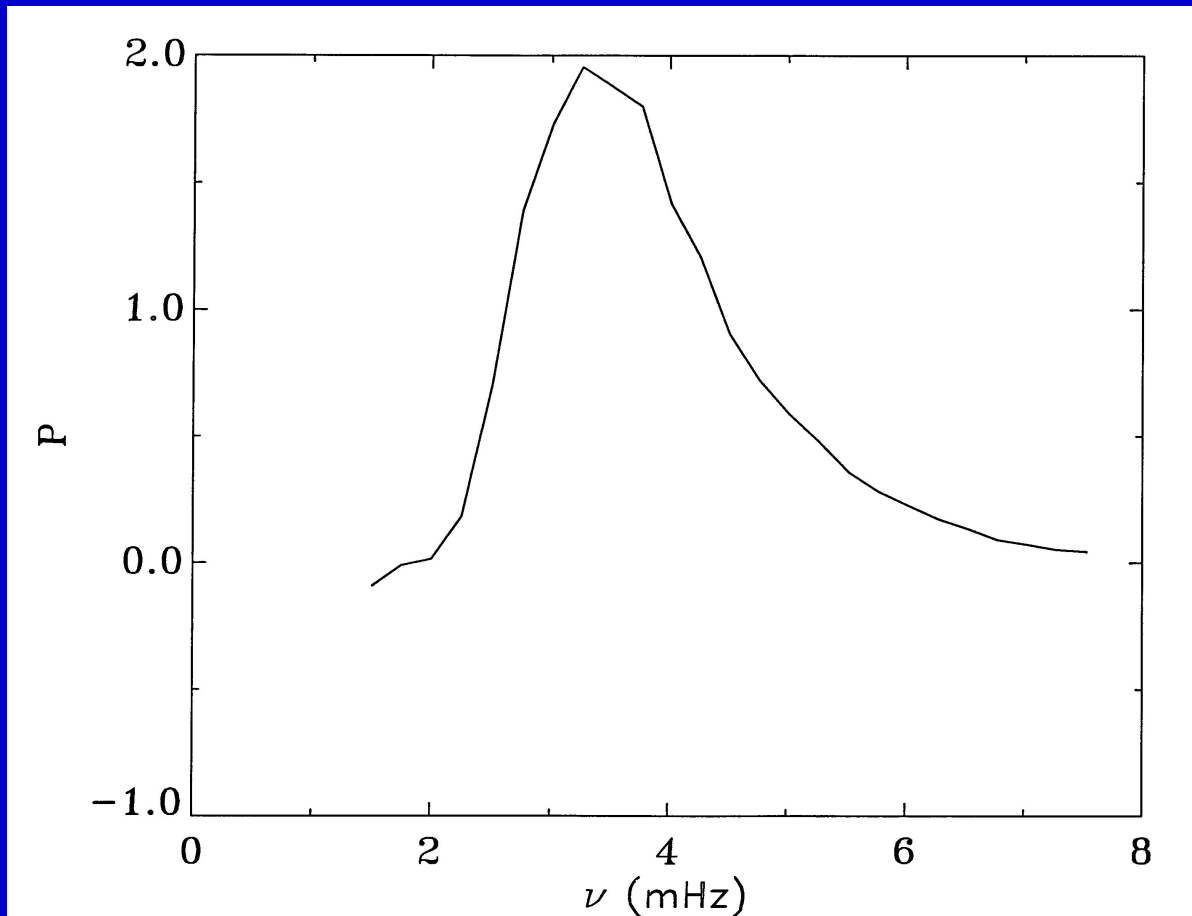
Averaged Seismic Flux Events and Averaged Granulation



Several hundred events
averaged after co-registering by
peak in seismic intensity.
Abrupt darkening characterizes
the rising phase of the events.
Note darker than average
intensity at all times.

Dip on leading edge is artifact &
trailing dip is downgoing flux.

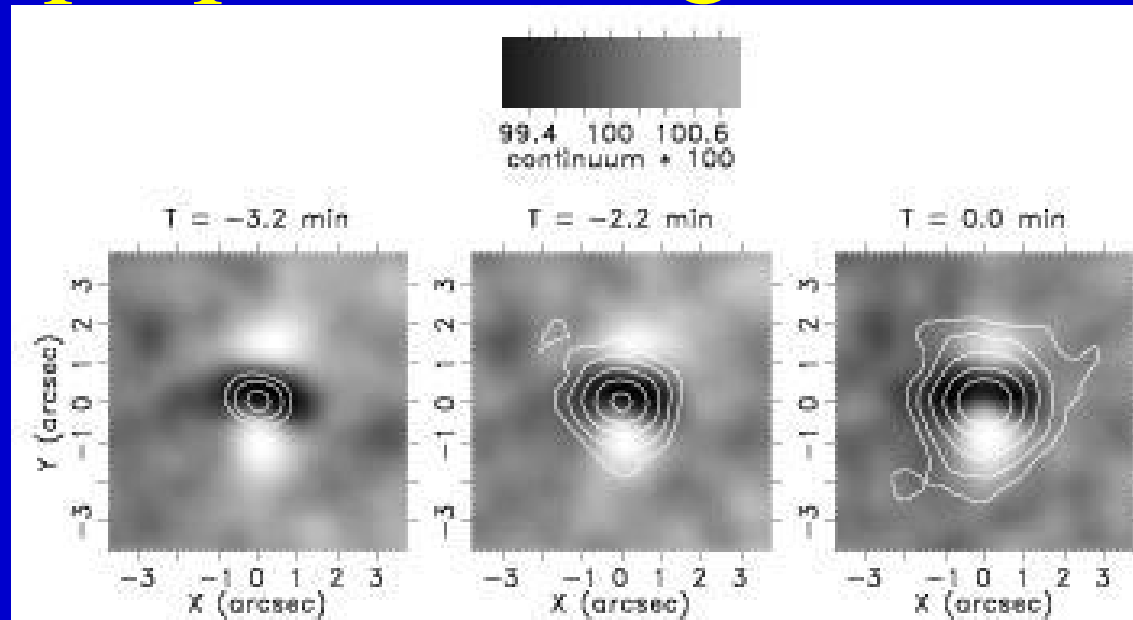
Frequency Binned Power Spectrum of Seismic Events



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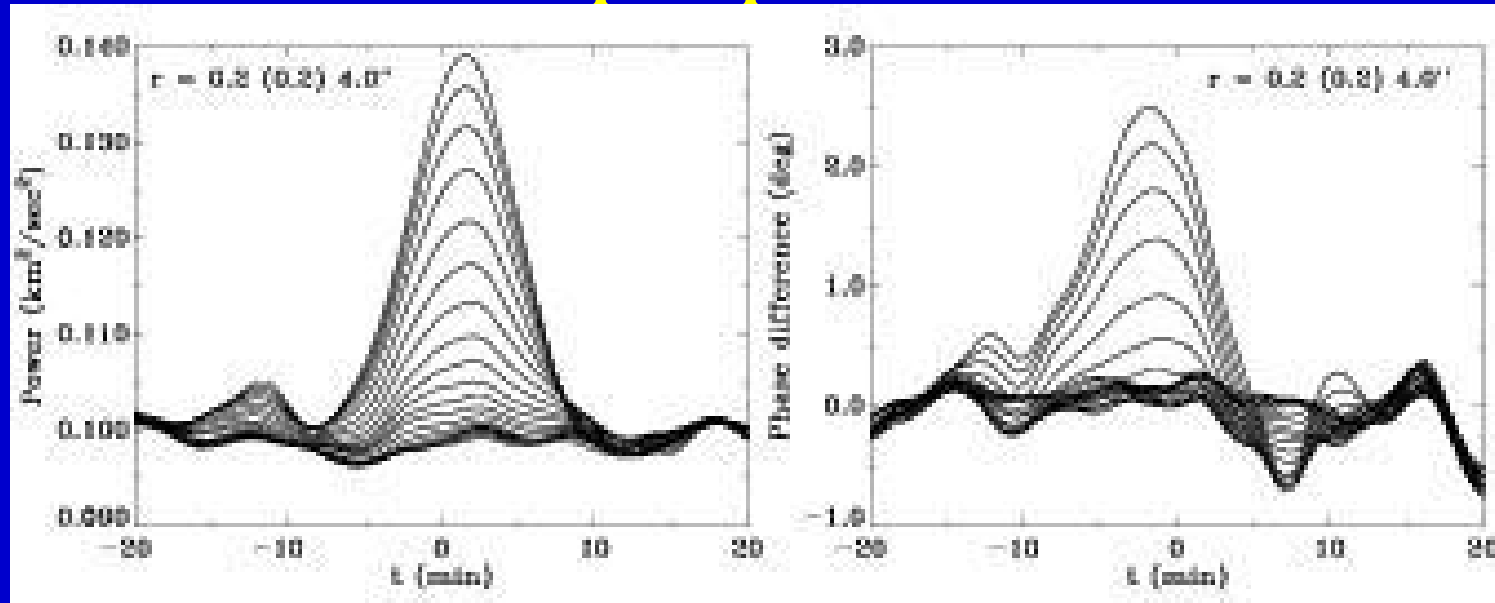
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Seismic Flux of 2000+ Superposed, Aligned Events



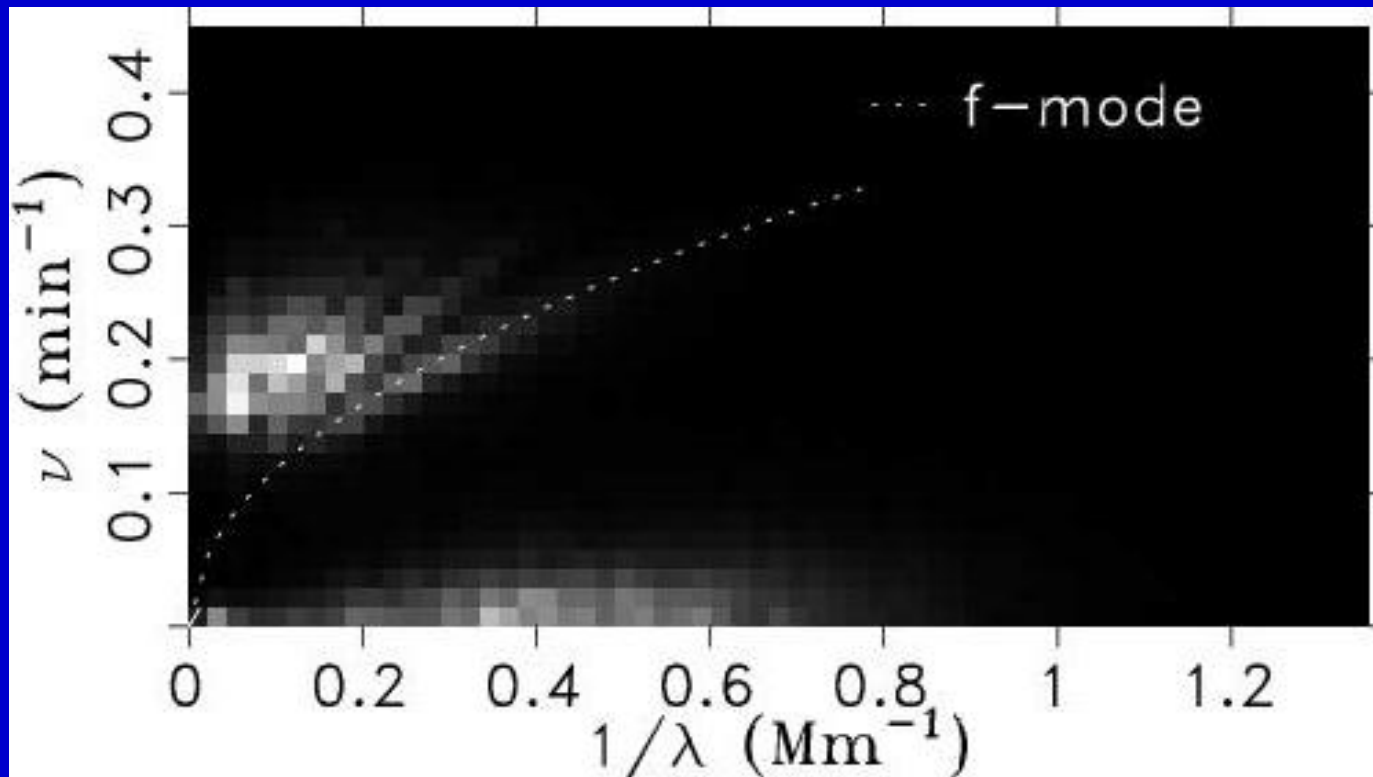
- X,Y&T=0 is peak flux for each event
- Dark lane oriented parallel to X-axis
—figure implies events originate in the dark lanes

Excess Power (V^2) & $\Delta\phi$ for 2000+ Superposed Events



- Beyond $r = 1.4''$ power is evanescent, while excess power is apparent out to $3.0''$. The evanescent power is slightly supersonic. Convective power has been filtered out.
- Travel is 30% faster over bright regions.

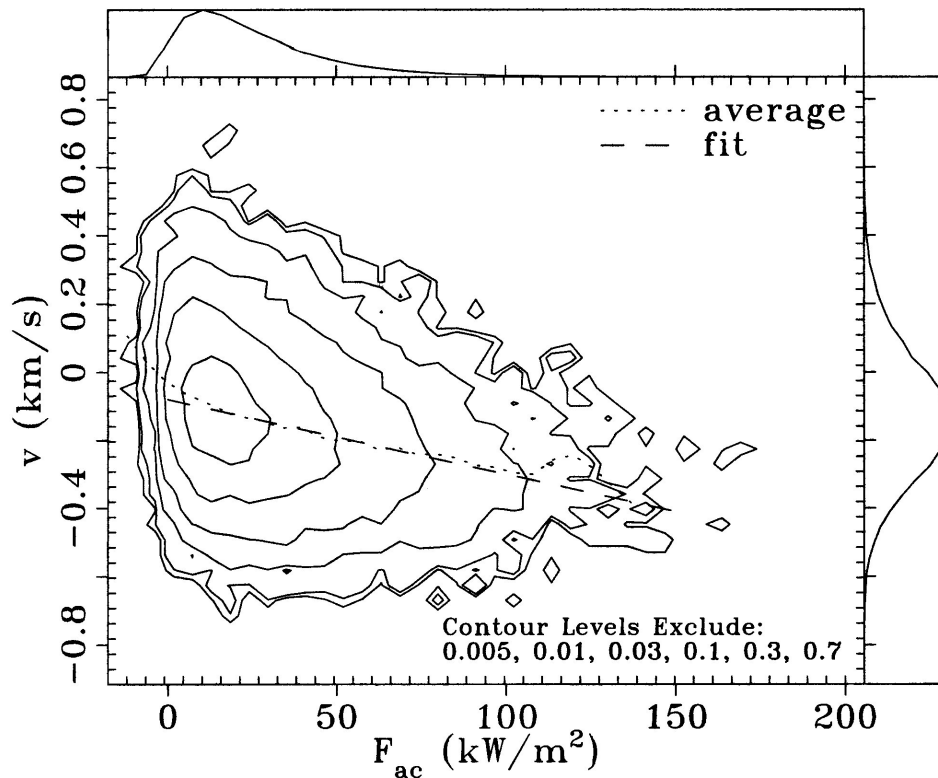
k- ω Diagram for 65 min Dataset



Why f-modes? Because excess power beyond $1.4''$ is evanescent, has 5 min period and group velocity of f-modes

- seismic power converted to f-modes—only normal modes that can contribute to excess power

Scatter Plot of Local “Seismic Flux” vs. Local Convective Velocity — Nature of the Source



- All “seismic flux” at all locations and times. Quotes because lowest fluxes consistent with noise.
- Linear (!) relation between convective velocity and seismic flux

Origin —Linear/Nonlinear

- Linear processes
 - rarefaction waves generated by collapse
 - & subsequent downgoing blob acting like piston
- Nonlinear processes
 - implosion of blob on itself
 - infall of material behind blob

What the Data Say — Linear Processes Drive Seismic Events

- Near center of a seismic event, speeds seem supersonic, suggesting a nonlinear component, but this probably reflects finite size of the events
- Nonlinear effects would take convective power and convert it to acoustic power— nonlinear effects seem small since acoustic and powers are well separated
- Further, in a linear theory, the subsonic velocities that should correspond to convective velocity do in fact correspond

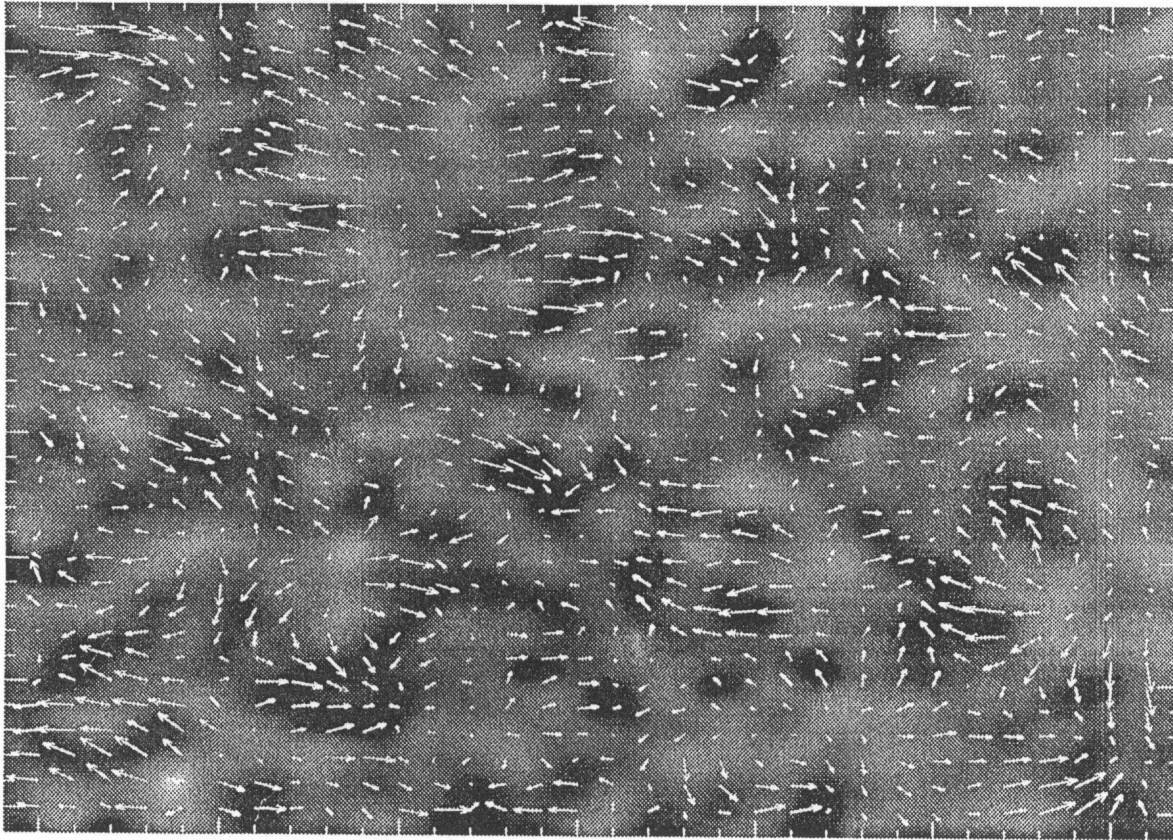
Meaning of Linear Relation Between Events and Local Convective Velocities

- $u \propto M^{2L+1} F_T \propto [(V_{\text{conv}})^{2L+1}] [\rho (V_{\text{conv}})^3]$: Lighthill picture in which seismic event depends on product of multipolarity, L , of convective Mach number and flux of local turbulence
 - for quadrupole source have $u \propto (V_{\text{conv}})^8$
- $u \propto [(V_{\text{conv}})^{2L+1}]$: Pressure driving, like downgoing, subsonic piston — our case
- Conclude source is monopole ($L=0$)

Are There Patterns to Regions of Largest Seismic Flux?

- Do “mesogranular” outflow regions have larger seismic flux because flows may leave regions with less heat being supplied from beneath?
- Do the magnetic fields suppress seismic events?

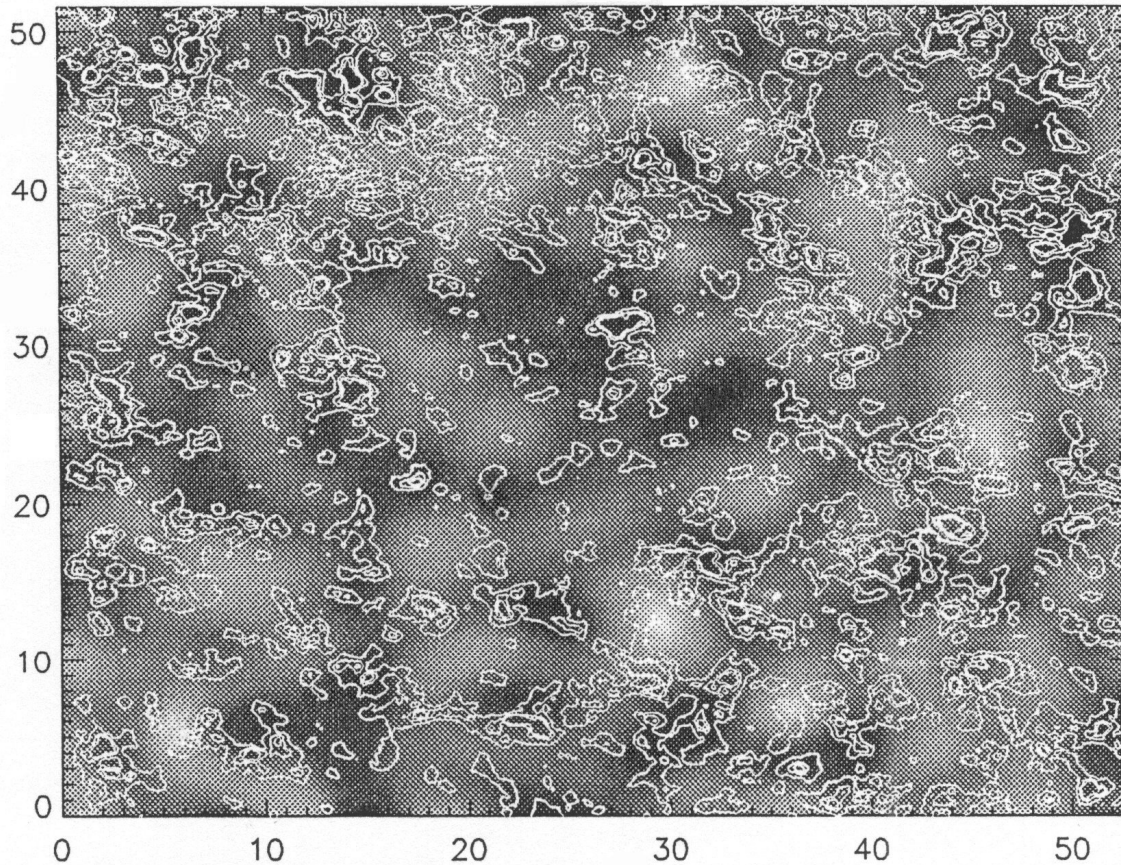
Mesogranular Field from Tracking Granular Flows



- 60 min mean flows taken as proxy for meso-granulation
- Outflows shown as bright in grayscale
- FOV is 50"x50"

Seismic Flux on Mesogranulation

– No Correlation

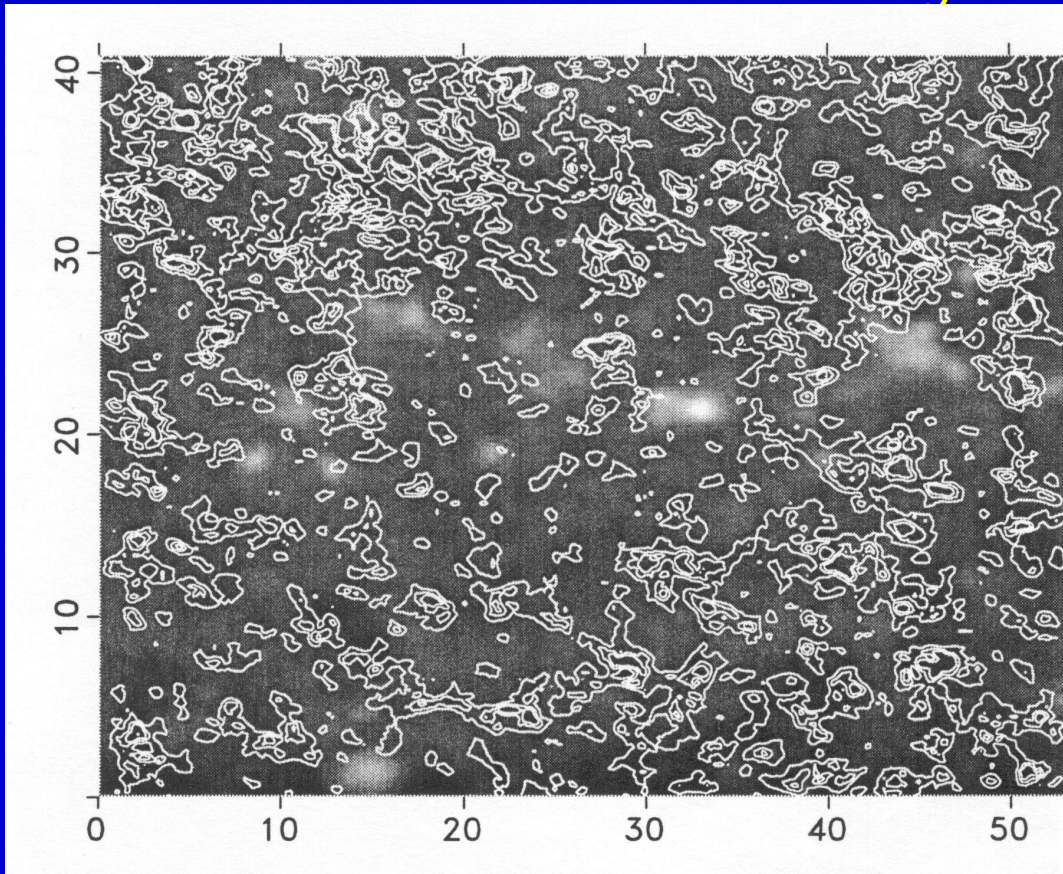


- Mean seismic flux in contours ($0.8, 1.2$ & 1.5×10^7 ergs/cm²/s, note: mean flux over FOV is 0.7×10^7 ergs/cm²/s) superimposed on “meso-granulation”
- No preference for large flux on outflows

Role of the Magnetic Field

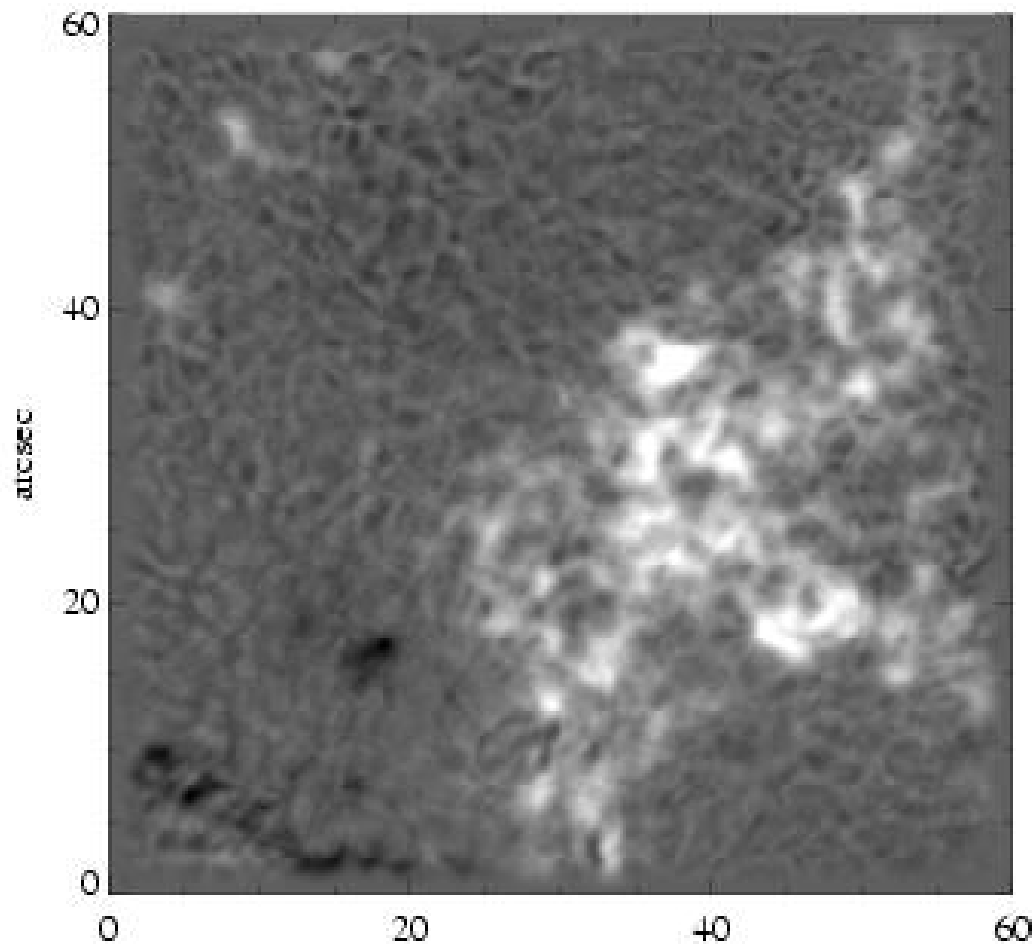
- Observed in “quiet” Sun region
- Use line weakening as a proxy for magnetic flux in current data
- Next, observe in area of moderate magnetic intensity
- Find the field inhibits seismic events

Seismic Flux vs. Weak Magnetic Field – Line Weakening as Field Proxy

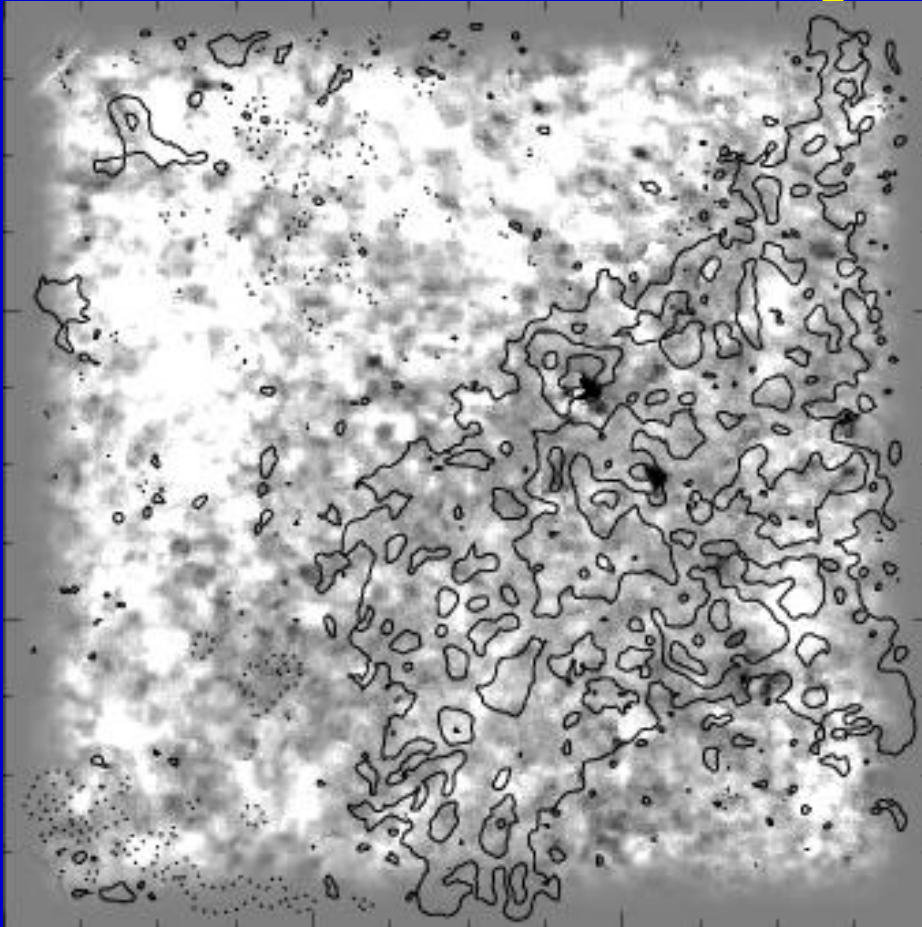


- Mean seismic flux over 60 min again shown as contours
- Brighter grayscale implies greater magnetic intensity

Mean Magnetic Flux for a Second 1 Hour Sequence



Magnetic Contours on Seismic Flux Grayscale



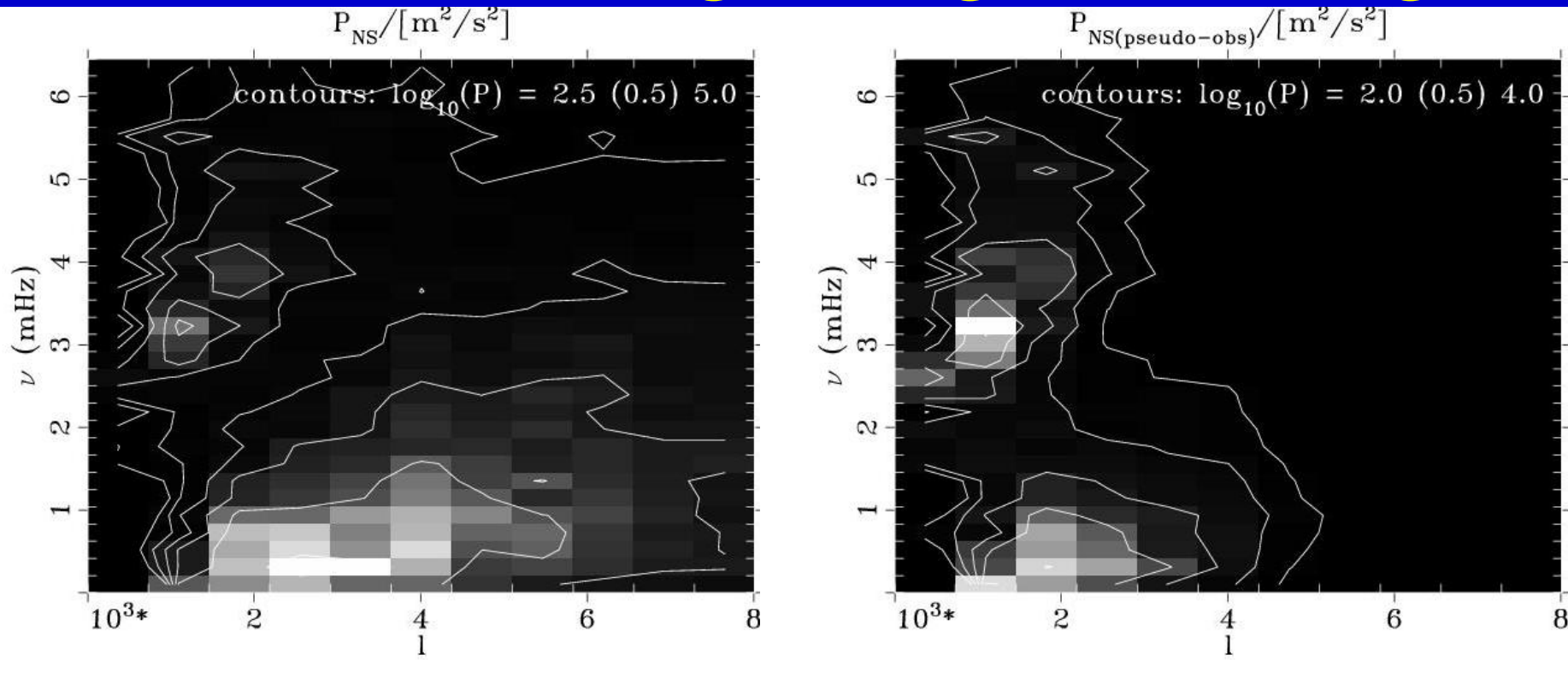
- 60 min mean seismic flux in grayscale on mean magnetic intensity contours
- Seismic flux nearly absent where the magnetic intensity is large

Simulations

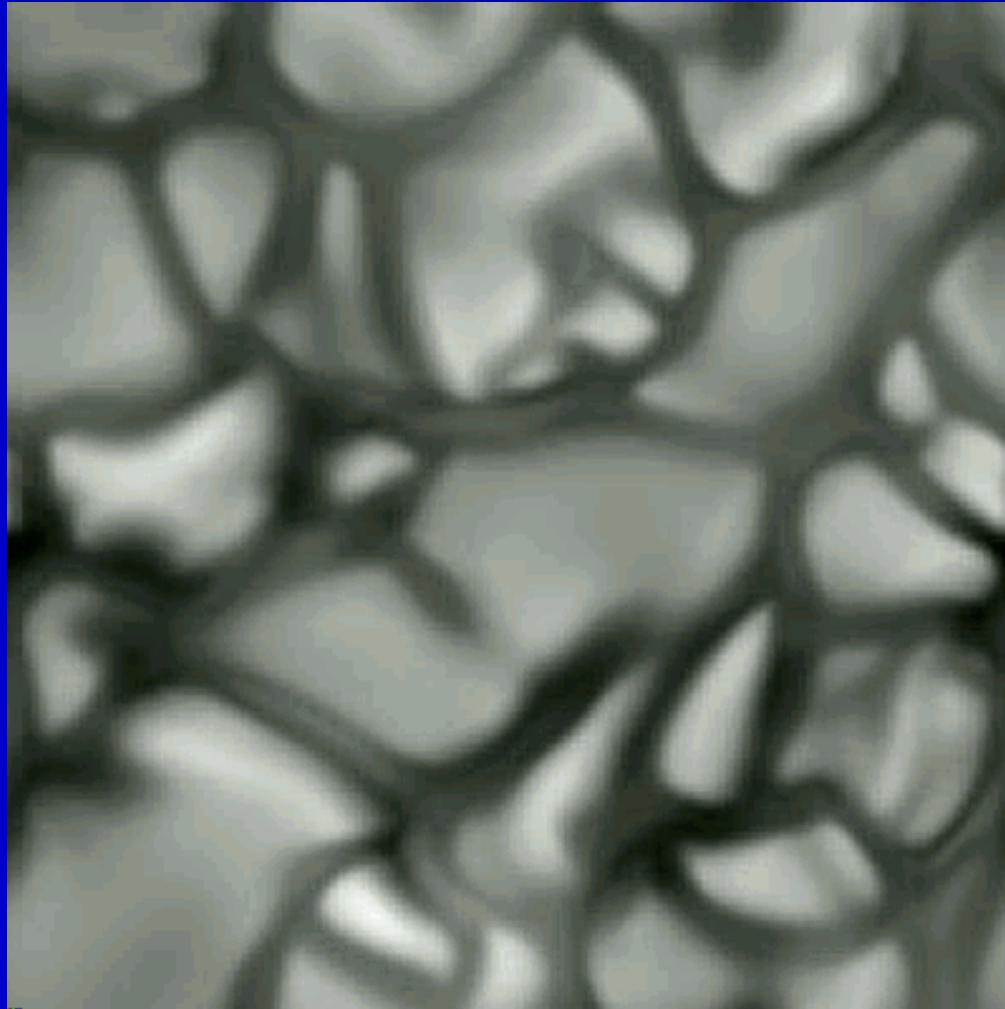
- Nordlund and Stein provide two sets of simulated line profile Doppler data for our reduction scheme — first is meant to simulate our time steps and altitude resolution, the second is the same as the first with the velocities being spatially degraded using $\text{PSF} \sim \exp(-0.45k)$ to incorporate seeing

k- ω Diagrams

Left) Simulations & Right) Simulations Degrading for Seeing



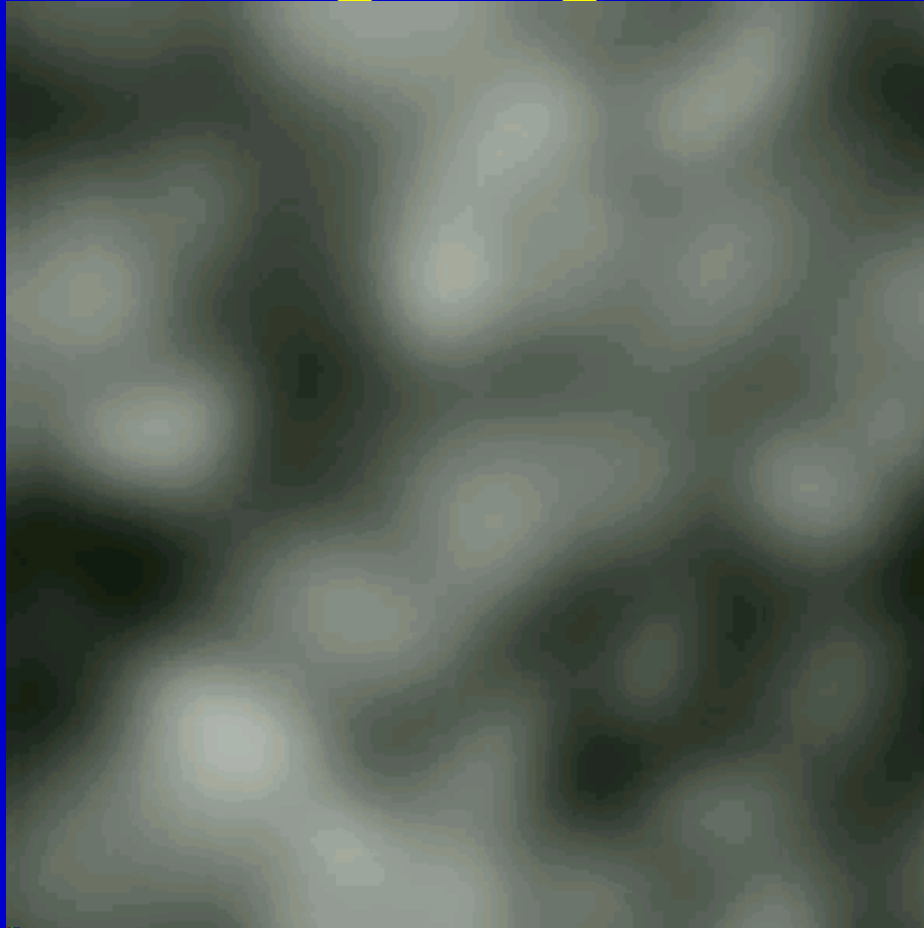
Convective Velocity Field—Filtered to Pass Convective Energy



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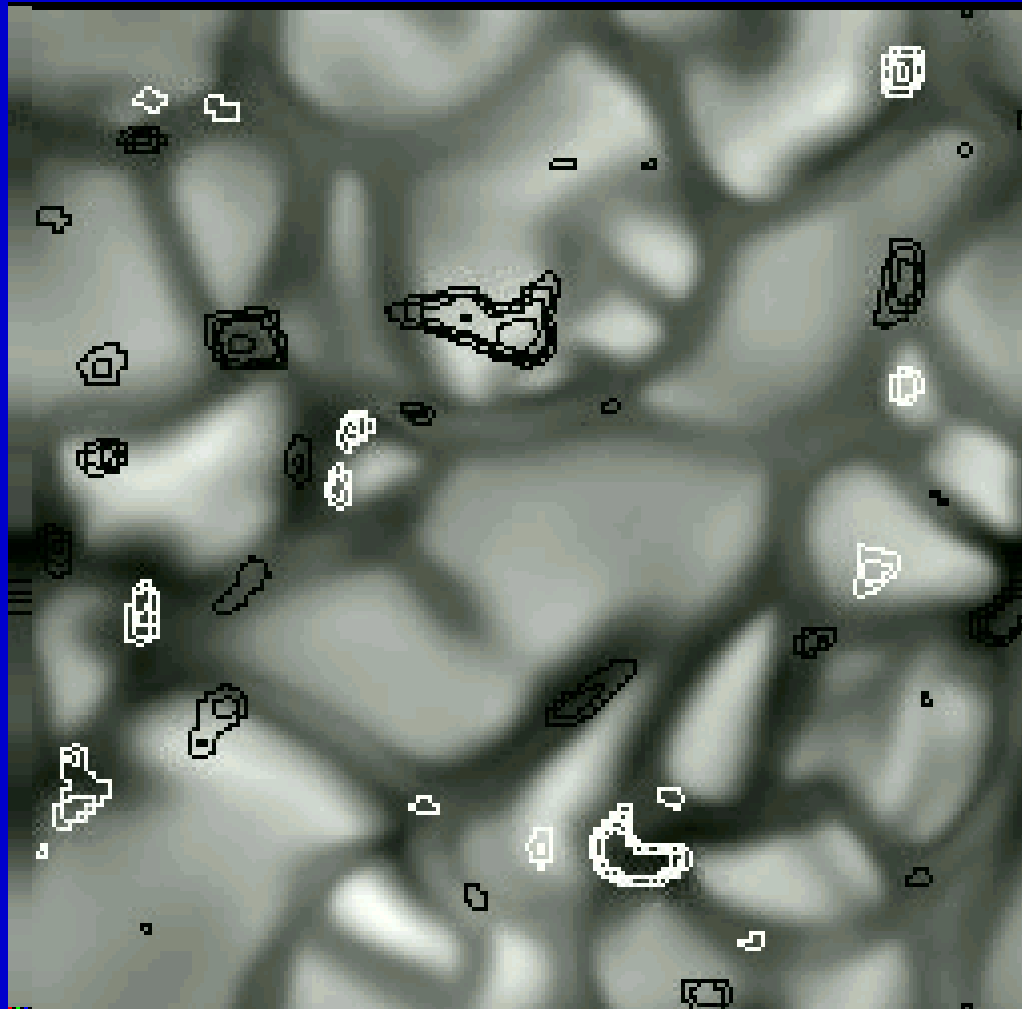
Convective Velocity Field — Seeing Degraded



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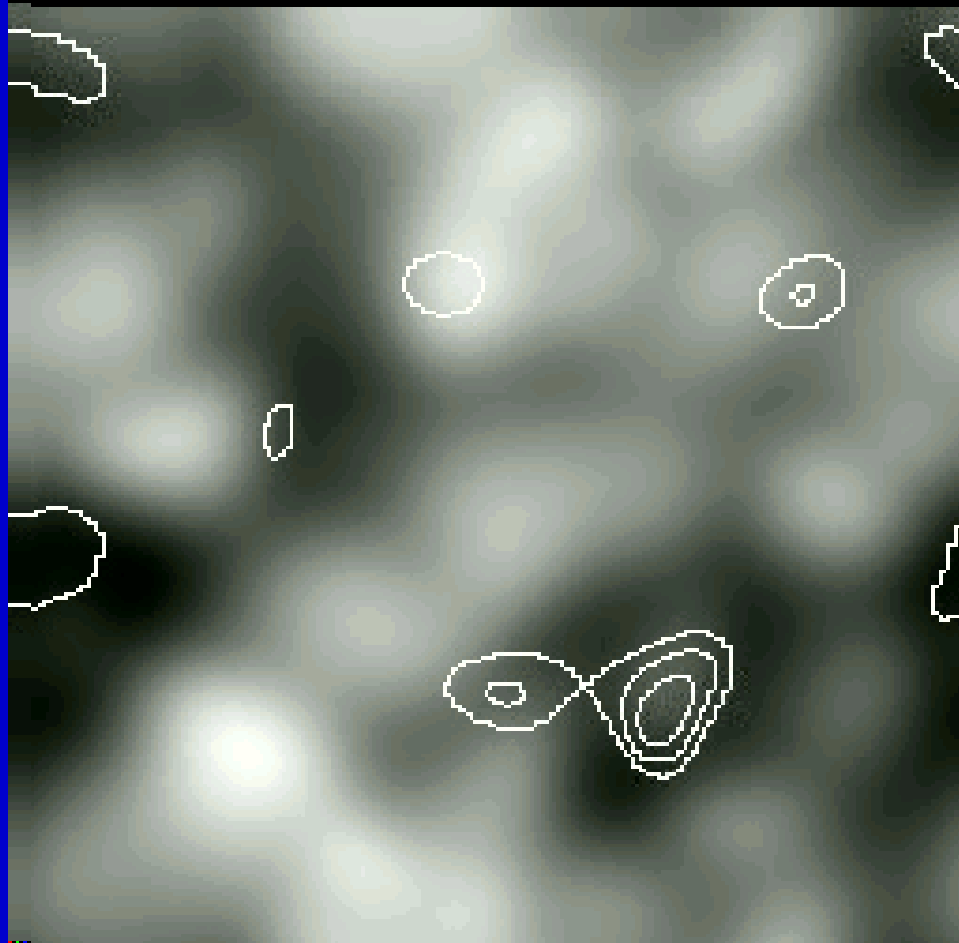
Seismic Flux on Granular Field



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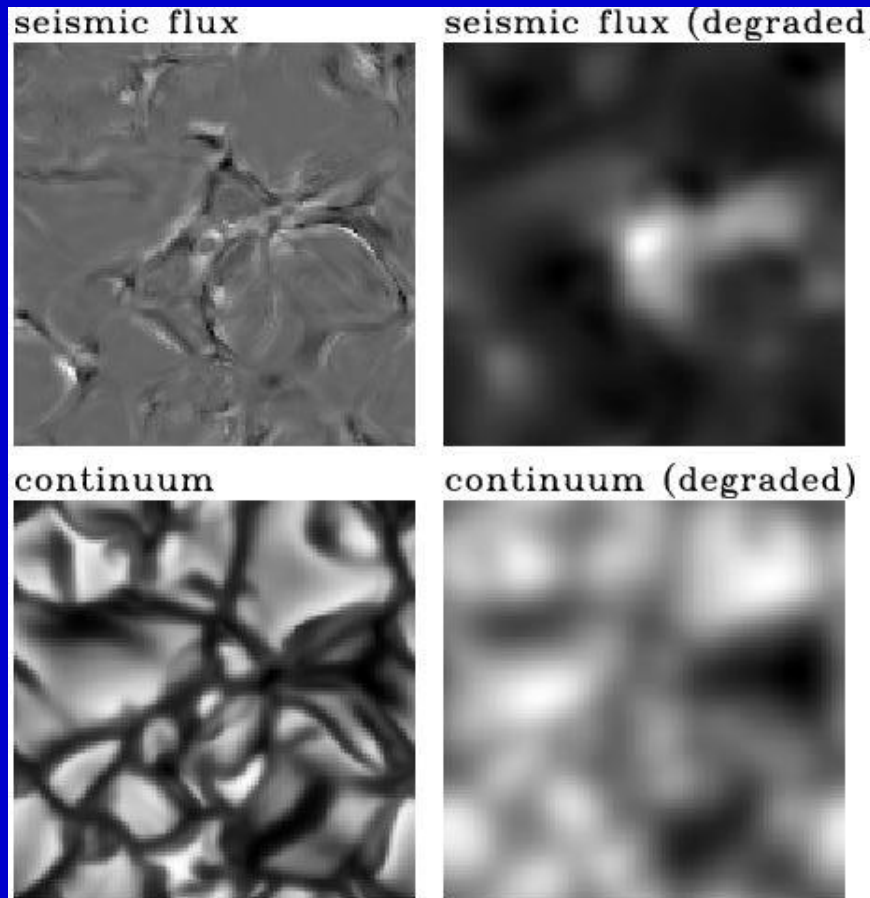
Seismic Flux on Granular Field — Seeing Degraded



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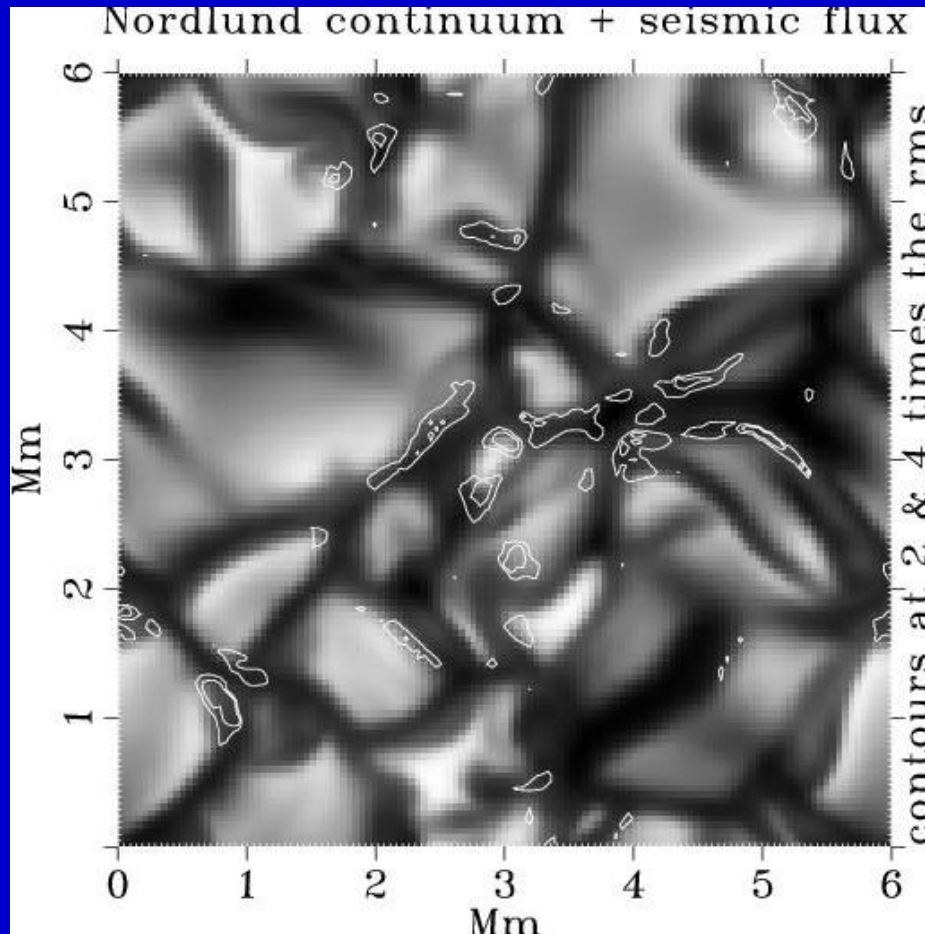
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Snapshot of Results from Reducing Simulated Line Profile



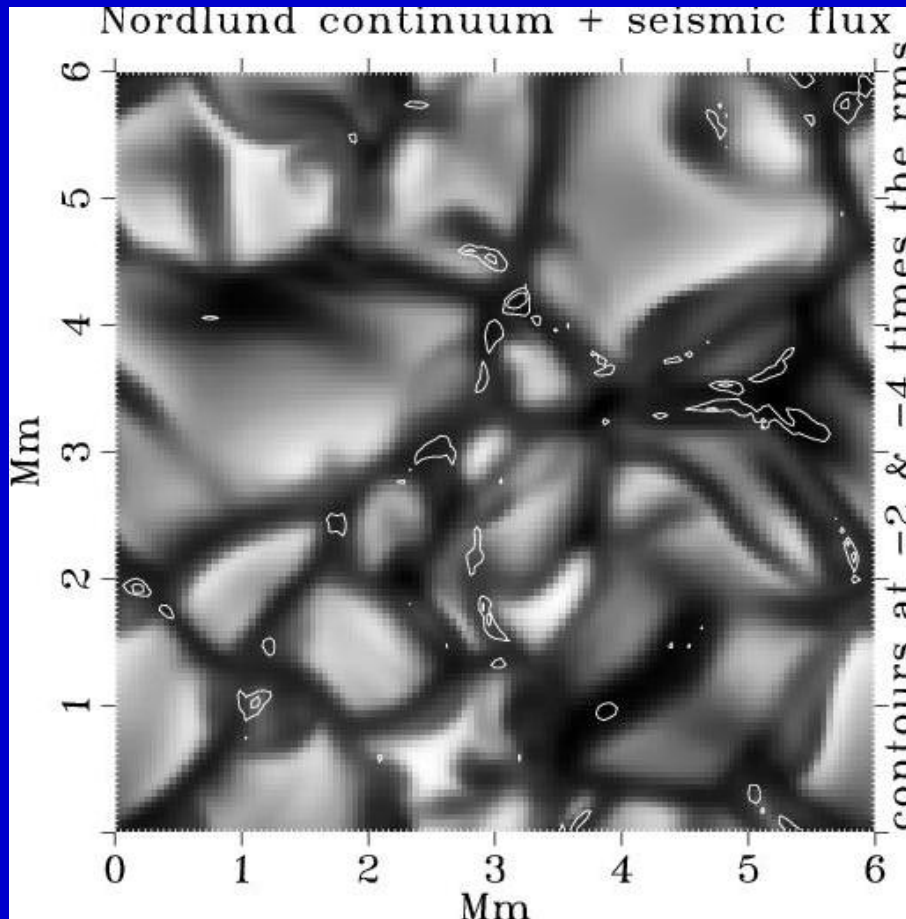
- Small bright granules at the center of the field of view collapse and bring down parts of neighboring granules & this is typical

Snapshot of Positive Seismic Flux Overlaid on Continuum



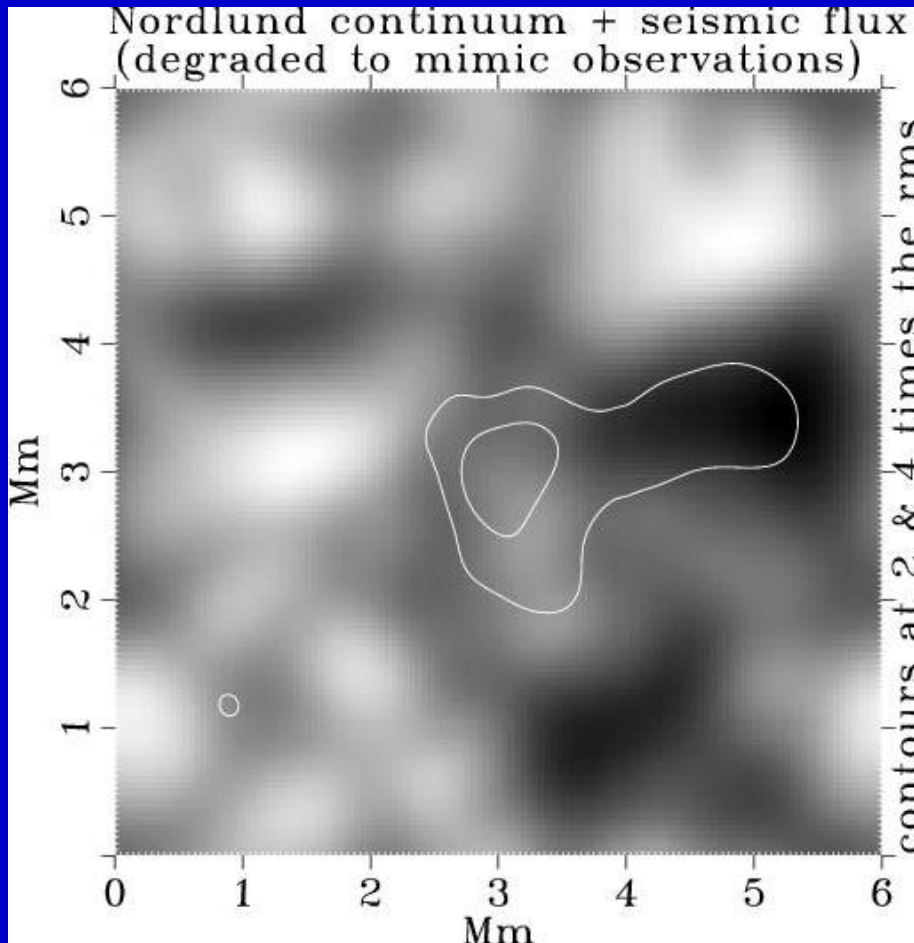
- Continuum in grayscale with seismic flux in contours
- Seismic flux confined to dark lanes

Snapshot of Negative Seismic Flux Overlaid on Continuum



- Continuum in grayscale with seismic flux in contours
- Seismic flux confined to dark lanes

Degraded Snapshot of Positive Seismic Flux on Continuum

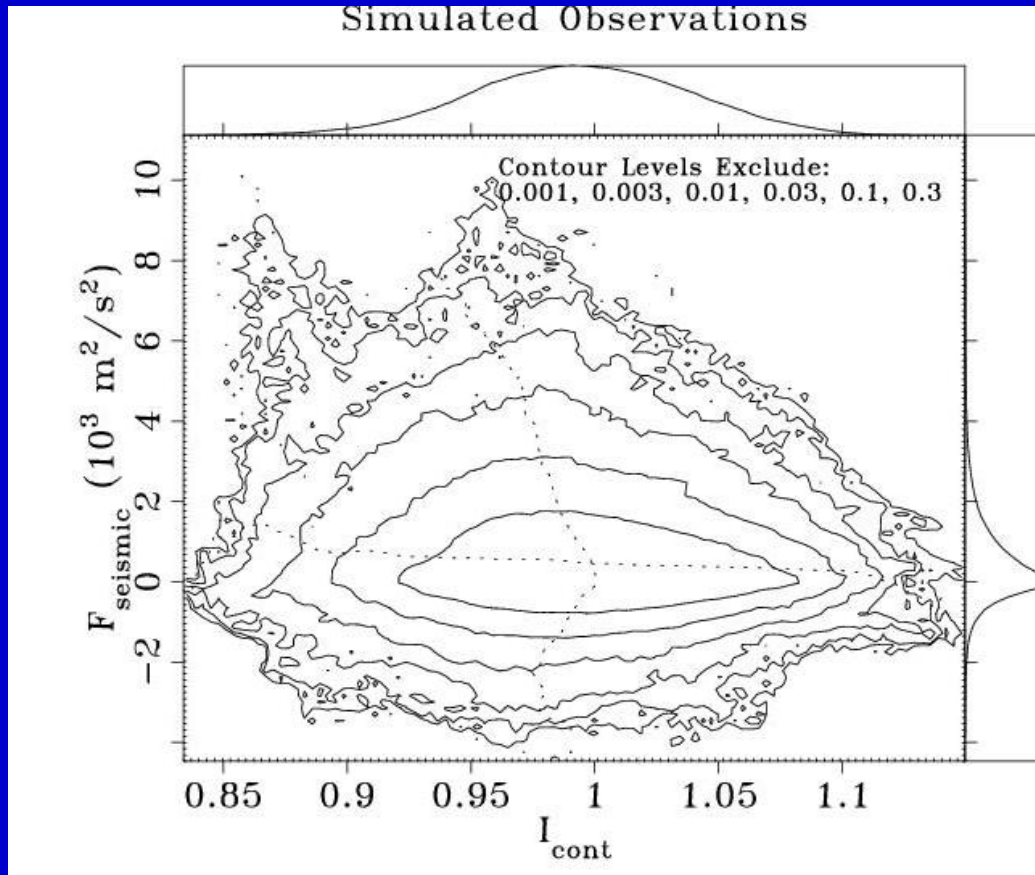


- From simulated line profile that has been degraded, where $\text{PSF} \sim \exp(-0.45k)$, to approximate seeing
- Seismic flux in darker areas

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Simulations Seismic Flux vs. Convective Velocity

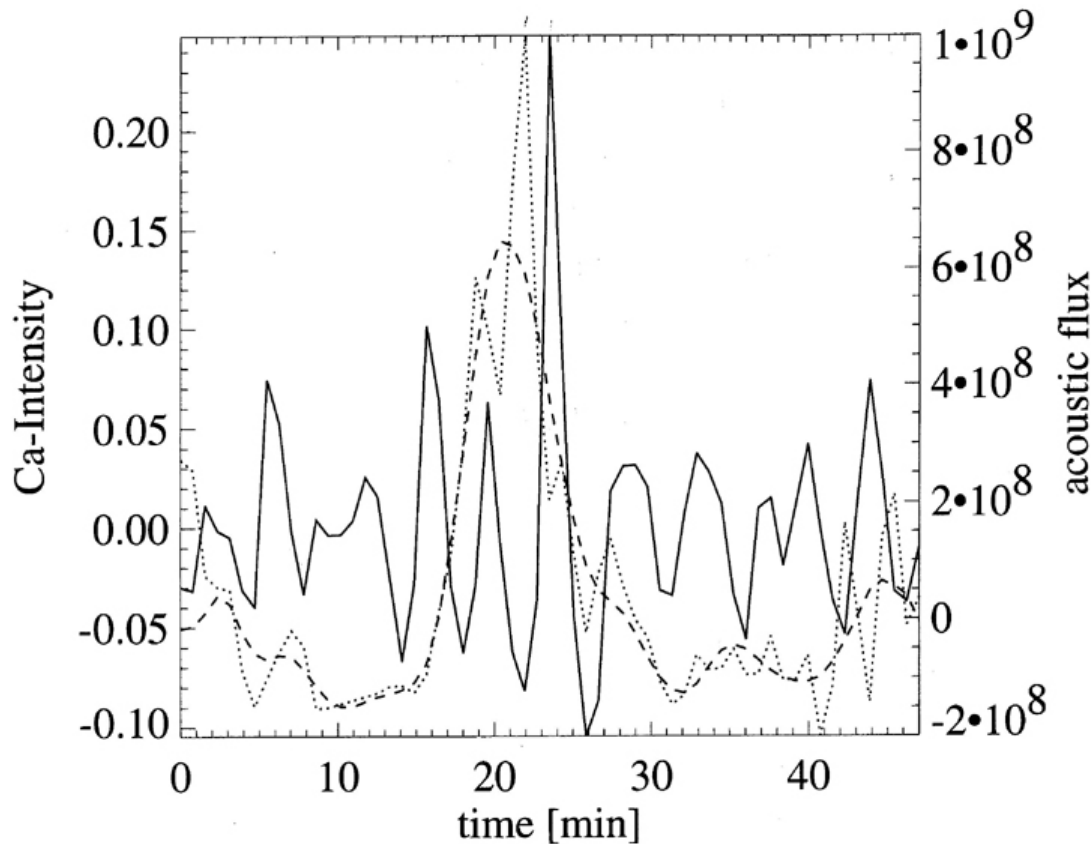


- Use simulations that are corrected for seeing
- See that there is a linear relation between convective downflow and seismic flux

Comparison of Simulated and Observational Results

- Seismic power in lanes and downgoing seismic flux follows upgoing flux, but downgoing flux is much weaker and too closely follows upgoing flux
 - boundary condition in simulations is that all waves reaching T_{\min} propagate out of the box
- Simulated events have a duration which is 2-3 times shorter than real events
 - ?

Seismic Events and Ca II K Brightpoints



- Dashed and dotted lines give the seismic flux with different temporal filters
- Solid line gives the brightpoint intensity for the same event

Ca II K Brightpoints

- Find strong correspondence between seismic events and oscillating Ca II K bright points. The ~ 2 min time lag corresponds to the time needed for disturbance to reach formation altitude of intermittent bright points and dissipate
- Seems quite probable that seismic events are extremely important (even crucial) in inducing bright point oscillations

The Future—High Resolution

- Degree of nonlinearity in turbulent generation of sound
- Very local helioseismology
- Nature of intermittent bright points
 - are seismic events the only source?
- Are there multiple sources?
 - one deeper as suggested by models?
 - use mode amplitudes thru the solar cycle
 - use mode ν -, l -dependences thru the cycle